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Security-constrained bi-level economic dispatch model for integrated natural gas and electricity systems considering wind power and power-to-gas process

Guoqing Li [a], Rufeng Zhang [a], Tao Jiang [a,*], Houhe Chen [a,*], Linquan Bai [b], Xiaojing Li [c]

[a] Department of Electrical Engineering, Northeast Dianli University, Jilin 132012, China
[b] Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville, USA
[c] Electric Operation Central Center of State Grid Changchun Power Supply Company, Jilin 130000, China

HIGHLIGHTS

- A bi-level dispatch model to minimize the total operation costs is proposed.
- Supply for both natural gas and electricity is dispatched economically and simultaneously.
- P2G is considered in short-term operation of the integrated energy systems.
- P2G may help wind power accommodation with reduced emission and gas consumption.

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ABSTRACT

Worldwide natural gas consumption has increased significantly, especially for power generation in electricity systems with the gas-to-power (G2P) process of natural gas fired units. Supply for both natural gas and electricity systems should be dispatched economically and simultaneously due to their firm interconnection. This paper proposes a security-constrained bi-level economic dispatch (ED) model for integrated natural gas and electricity systems considering wind power and power-to-gas (P2G) process. The upper level is formulated as an ED optimization model for electricity system, while the lower level is an optimal allocation problem for natural gas system. Natural gas system is modeled in detail. In addition, the security constraints and coupling constraints for the integrated energy systems are considered. The objective function is to minimize the total production cost of electricity and natural gas. The lower model is converted and added into the upper model as Karush-Kuhn-Tucher (KKT) optimality conditions, thus the bi-level optimization model is transformed into a mix-integer linear programming (MILP) formulation. Numerical case studies on the PJM-5bus system integrated with a seven-node gas system and IEEE 118-bus system integrated with a modified Belgian high-calorific gas system demonstrate the effectiveness of the proposed bi-level ED model.

1. Introduction

As one of the most important fossil fuels, the natural gas consumption in the world has increased significantly in the last decade, especially for the use in power generation. By 2030, the gas-fired generation is expected to increase by 230% [1,2]. At the same time, the number of natural gas fired generating unit (NGFGU) installations has grown dramatically, which results in the tight coupling between the electricity systems and the natural gas systems [3]. Compared with conventional coal plants, NGFGUs have higher economic efficiency, lower environmental emissions and faster response capabilities [4].

Gas-fired power plants provide a linkage between natural gas and power systems. Due to the interdependence between electric power and natural gas systems, the economy and reliability of the two energy sectors would be influenced by each other directly [5,6]. On one hand, the price of natural gas fluctuates, leading to the change of operating cost of NGFGUs [7], and thus affecting the economy of power system. On the other hand, the security regions of electric power systems and natural gas systems cannot

* Corresponding authors.
E-mail addresses: tjiang@nedu.edu.cn (T. Jiang), chenhouhe@nedu.edu.cn (H. Chen).

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Nomenclature

GSF_e	generation shift factor
t/T	time period
F_{nj}	pipeline flow
GSFgas/GSF	gas/generation shift factor
$\pi n/\pi j$	nodal pressure
c_i	bid of generating units
$P_{i,t}$	power output of generating units
$Limit_{gas,nj}/Limit_l$	pipeline/transmission line limits
$\eta_{i,sr}$	cost coefficient for spinning reserve
η_{G2P}	efficiency of NGFGU
$P_{wind,t}^{forecast}$	wind power forecasting output
D_t	electricity load
P_{imin}/P_{imax}	lower/upper limits of generation
R_d	reserve for wind power
R_{down}/R_{up}	spinning reserve requirement
$S_{m,\min}/S_{m,\max}$	lower/upper limits of gas supply
$\lambda/\omega_m^{\min}/\omega_m^{\max}/\mu_{nj,t}^{\min}/\mu_{nj,t}^{\max}$	dual variables
$\nu_{\mu,nj,t}{}^{\min}/\nu_{\mu,nj,t}{}^{\max}/\nu_{\omega,m,t}{}^{\min}/\nu_{\omega,m,t}{}^{\max}$	auxiliary binary variables
m, n, j	natural gas system nodes
M/N	number of gas supply and generating units
C_{nj}	pipeline constant
NG	number of natural gas nodes
S_m/GL	natural gas supply/load
c_{wind}	bid of wind farm
$Price_{m,gas}$	gas price
$P_{wind,t}$	dispatched wind power output
π_{cw}	cost coefficient for wind curtailment
η_{P2G}	efficiency of P2G
$E_{P2G,t,gas}/S_{P2G,t,gas}$	energy/volume of natural gas from P2G
$D_{m,t}$	electricity load for P2G
$Ramp_i^u/Ramp_i^d$	ramping rate of generating unit
$\overline{S_{P2G,gas}}$	upper volume limits of gas from P2G
$GL_{P2G,t,gas}$	virtual natural gas load of P2G
$GL_{\min}/GL_{\max}$	lower/upper limits of gas load
$M_\omega^{\min}/M_\omega^{\max}$ $M_\mu^{\min}/M_\mu^{\max}$	large enough constants

be considered independently due to their inherent interdependency [2,8]. Therefore, the economic operation problem of integrated natural gas and electricity system should be analyzed simultaneously. The security constraints of both electricity and natural gas systems should be taken into account.

For the optimal operation of integrated natural gas and electricity systems, the studies on single- or multiple-period operational optimization are investigated in [3,4,7,8,13,14,15]. In the conventional optimal operation of electric power systems, the dispatch of NGFGUs along with other thermal sources such as coal, oil and nuclear does not consider the fuel supply constraints. However, with the growth of the natural gas market, the limit of the natural gas network with the increasing demand of NGFGUs becomes an issue that is not negligible [9]. In [10], the authors developed an algorithm to solve the problem of optimal operation of a gas transmission network. The natural gas flow network is modeled in [2–4,11] with daily and hourly limits on gas supply, demand, pipeline and storage. An approach for long-term expansion planning of combined gas and electricity networks is proposed in [12], which determines the timely and efficient allocation of resources (pipes vs. electricity transmission lines) in the expansion of energy networks. An operating strategy for short-term scheduling of gas-electricity integrated energy systems is proposed in [13] considering demand response and wind uncertainty. In [7,14,15], stochastic optimization models are proposed to address the uncertainties of various system components. In [16], optimization problems in natural gas transportation systems are analyzed, which demonstrate the necessity of optimal allocation of natural gas. However, in these existing literatures, economic dispatch of the two energy sectors is done ignoring the optimal allocation of natural gas supply.

To realize the optimal allocations of both electricity and natural gas, bi-level programming can be an effective method. In previous works, bi-level programming has been applied to optimal operation problems of power system [17–21]. In [17], the interactions between generation and load are considered in microgrid, in which the upper level is the energy-saving dispatch model and the lower level is the load control optimization model. Various methods of optimal operation of power system considering renewable energy, energy storage or electric vehicle are formulated as bi-level models in [18–20].

For power systems integrated with large-scale renewable energy, significant amounts of renewable energy generation are curtailed due to security restrictions. In this context, there has been widespread discussion of the power-to-gas (P2G) process whereby electrical energy can be converted to hydrogen (H_2) or synthetic natural gas (SNG), stored and recovered at a later time through combustion to generate low-carbon electricity and/or heat [22,23]. The P2G process not only helps avoid waste of renewable energy in electrical system due to system constraints, but also realizes the two-way coupling for the integrated gas and electrical systems, as shown in Fig. 1. Surplus renewable energy due to system constraints in electricity systems can be utilized to produce hydrogen or synthetic natural gas by the P2G process. From the perspective of long-term operation, the benefits of P2G are investigated in [23] in terms of wind curtailment and carbon emissions displacement, economic cost-saving associated with natural gas production, and congestion relief in both the gas and electrical networks. Grond et al. [24] analyzed the potential of a grid balancing system based on different combinations of traditional gas tur-

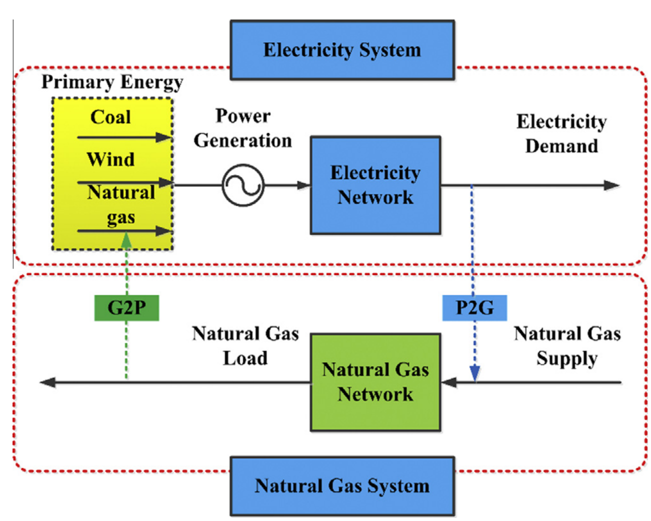

Fig. 1. Integrated natural gas and electricity network considering wind power and P2G.

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